ABSTRACT
As the new era dawns in wireless information systems, mobile satellite services (MSS) are emerging as an integral component in what has become the turn-of-the-century global communication network. It is generally agreed that the universal personal communication paradigm is the confluence of terrestrial-based and satellite-based systems. PCS users will neither know nor care if their calls are being carried by satellite or cellular. Unlike their terrestrial-based counterparts, the MSS, with their global blanket coverage, are truly able to realize the vision of communications from anywhere at any time for people on the move. The MSS are also being used in developing countries without existing wireline networks to provide rapid, ubiquitous telephone service. This article provides an overview of mobile satellite systems and concepts. The materials presented are geared toward a broad audience with engineering or management backgrounds.

PCS Global Mobile Satellites

Farrokh Abrishamkar, Lucent Technologies/Bell Labs Innovations
Zoran Siveski, New Jersey Institute of Technology

The Federal Communications Commission (FCC) has now completed its public auction of 120 MHz of spectrum of personal communications services (PCS) licenses A, B, and C, for a price tag of about $20 billion. The staggering cost of this spectrum indicates why wireless communications operators and cellular providers are accelerating the timeline to bring PCS to the public. Technologies and systems associated with this evolving wireless information network may be categorized as satellite-based, terrestrial-based, or hybrid [1, 2]. The convergence of satellite- and terrestrial-based systems is not too distant. In fact, the industry is actively involved in the development of dual-mode, integrated satellite-terrestrial (e.g., Global System for Mobile Telecommunications — GSM) wireless services. Satellites are increasingly becoming an integral component of turn-of-the-century global personal communication systems in the form of IMT—2000 (International Mobile Telecommunications after the year 2000, formerly Future Public Land Mobile Telecommunications System — FPLMTS) and Universal Mobile Telecommunications System (UMTS) [2]. In realizing PCS requirements, the development of the most recent generation of mobile satellites reflects the transition from network-based to user-based and from physical channel to logical channel (advanced intelligent network, or AIN) mobile communications systems.

Commercial communications by satellite, with global access predating what is currently known as PCS by about three decades, provides various categories of service. Examples of satellite systems include fixed satellite service (FSS), direct broadcast satellite (DBS), aeronautical mobile satellite service (AMSS), land mobile satellite service (LMSS), mobile satellite service (MSS), and many more [3]. Of the systems mentioned, MSS are the primary satellite systems designated to provide the PCS class of services. The focus of this article is to provide a brief overview of the technologies and systems associated with the broad categories of global MSS systems.

Satellite technologies have undergone a transition from the passive "bent-pipe" state to an active system with on-board switching and signal processing capabilities. In defining the confluence of terrestrial and space technologies, in the early 1990s the European project COST 227 undertook a study where satellites were to supplement terrestrial services in sparsely populated regions using a specific priority scheduling strategy [4]. While the MSS community has somewhat moderated its initial assessments of replacing or competing with cellular service, it is now expected that MSS will alleviate the terrestrial system in congestion periods, provide service in case of disaster or disruption in cellular systems, and service vast and remote geographical areas where installing terrestrial-based systems is not economically viable [5].

ORBITAL SELECTION AND FREQUENCY ALLOCATION

The MSS is designed not only to meet the basic requirements associated with third-generation wireless information networks and PCS, but also to eventually integrate with future systems such as FPLMTS and UMTS. The mobile satellites' fundamental parameters are orbit selection, satellite payload, coverage, frequency band, and operating license. The last two parameters represent the regulatory and political dimensions of system planning. The frequency acquisition process involves national and international standards, regulatory consensus, spectrum availability, and national interest. The operating license is a key to create a competitive environment, particularly as the satellite business becomes more widespread. The FCC, for instance, is in the process of allowing non-U.S. systems to compete against U.S. companies in the United States provided that U.S. satellite systems are allowed to have "effective competitive opportunities" in these countries [6]. Orbit selection probably has the most fundamental impact on all other system design aspects. The payload identifies the

This article presents a snapshot of rapidly changing systems. The basic information, however, should be a useful starting point for the reader interested in mobile satellites.
appropriate system capacity given a particular architecture. The coverage determines the number of spot-beams and their corresponding footprints. The last category, frequency band, which deals with the regulatory dimension of the system, impacts channel fading rapidity and, consequently, system performance. This section describes system divisions, trade-offs, and concepts involving orbital selections.

**SYSTEM CATEGORIZATION**

In the broadest sense, mobile satellite systems are identified as either geostationary earth orbit (GEO) or non-geostationary orbit (NGSO) satellites. Mobile satellite systems may also be partitioned along the correlated categories of frequency allocation and orbital deployment, in addition to their service classifications. The NGSO category is divided into big low earth orbit (LEO) and little LEO, also referred to as non-voice, non-geostationary (NVNG). Big LEO satellites are characterized by their larger size and their capability to provide near-toll-quality voice in addition to other services like data, facsimile, RDSS, and others. Big LEO satellites are implemented as medium earth orbit (MEO) (intermediate circular orbit, ICO), highly elliptical orbit (HEO), or LEO satellites.

The little LEO designation, on the other hand, reflects a small size (low mass) and the capability to provide only low data rates (on the order of kilobits per second). The choice of frequency-based partitioning of these systems typically suggests the system service features. Systems operating below 1 GHz, for instance, lend themselves to NVNG satellites with low data rate capabilities. Such partitioning is also reflected in the structure of the FCC World Radio Conference (WRC) advisory committee. Interim Working Group (IWG)-2A deals with issues involving systems operating below 1 GHz. IWG-2B is responsible for systems along the L-S band (1–3 GHz), which may be deployed as either big LEO or GEO, including feeder links (except for Ku feeder links). Finally, IWG-2C deals with Ku-band satellite issues.

**ORBITAL TRADE-OFFS**

The following discussion on orbital trade-offs is based on the material in [7, 8]. The GEOs, which are seen as stationary from earth, in principle require three satellites (at an altitude of about 35,800 km) to provide complete uninterrupted global coverage. However, since the elevation angle falls below the minimum required 10 degrees, they cannot provide coverage in far north and far south latitudes. The main advantages of GEOs are configuration simplicity, modularity (one covers a single region, while three cover the whole planet), an extremely wide spot-beam footprint (the subscriber will not have to switch spot-beams during a call), relatively time-invariant satellite–ground terminal geometry, a simple space segment control system, and fixed propagation delay (but very large, i.e., 260 ms/hop).

GEO system disadvantages include power-limited links (the prohibitive distance together with spectrum limitations make the channel band-limited and power-limited, e.g., the American Mobile Satellite Corporation (AMSC) GEO system operates with portable terminals rather than handheld telephones), excessive propagation delay for voice and automatic response request (ARQ)-based packet data (the double-hop 520 ms far exceeds the maximum 100 ms delay recommended by the International Telecommunications Union — Telecommunications Standards Sector, ITU-T), and the inability to cover polar regions. GEO systems may be deployed for either global or regional coverage. The latter has a reduced coverage area requiring spot-beams with a smaller solid angle, which results in larger antennas gain. The gain in transmission link margin generated by coverage reduction may be shared by the mobile and satellite.

LEOs are deployed in either circular or elliptical orbits (at altitudes of 500–2000 km) below the two Van Allen radiation belts (1500–5000 and 13,000–20,000 km) which are harmful to the solar cells and on-board electronics, but high enough to avoid atmospheric drag. A lower orbital altitude translates into a larger number of satellites, an increase in the minimum elevation angle, a shorter visibility period (a few minutes), and more frequent interbeam as well as intersatellite handoffs. The advantages of LEOs may be summarized as much better link margin, much lower propagation delays, easier launch, and the ability to support handheld terminals. The problems are a large number of satellites, more complex on-board control subsystems, less satellite dwell time, and more frequent handoffs (10 min/intersatellite and 1–2 min/interbeam), a much larger Doppler shift, and lower system modularity with a higher cost. On the plus side, in the event of a single satellite loss, unlike the GEOs, the large satellite set will only experience a graceful degradation in overall performance. The transition from the GEO class large satellites to the smaller NGSO satellites, although a trend reversal in communication satellites, has economic justifications. In many applications a large constellation of NGSO small satellites appears to be more cost-effective than the single large one.

The MEO (ICO) satellites are deployed in circular orbits at an altitude of about 10,000 km between the two radiation belts, requiring a typical constellation of about 10–15 satellites with an average visibility of 1–2 hr/satellite. ICO offers an orbital and architectural compromise between LEO and GEO. For example, ICO propagation is less than GEO and more than LEO; it requires less frequent handoffs than LEO, but more than GEO. The HEO system is deployed in elliptical orbits with a visibility of about 4–8 hr. The principles of Kepler's second law govern the motion of HEO satellites. They move slowest when positioned farthest from the earth (apogee), thus providing extended coverage above such a region, and they move fastest when closest to the earth (perigee). As a result of the apogee altitude, however, the propagation delay and path loss are comparable to those of GEO. Other advantages of HEO include a high elevation angle (55–60 degrees, e.g., good for European coverage) and a flexible system design. The disadvantages are a lower link margin than GEOs (very high altitude), large on-board antennas (6 m for L-band), a large Doppler shift, and a shorter satellite lifetime due to periodically crossing through the Van Allen radiation belt.

**GEO SATELLITES**

The history of commercial mobile satellites is marked by developments at the International Maritime Telecommunication Satellite Organization (INMARSAT), a multinational organization affiliated with the United Nations International Maritime Organization with membership in excess of 60 countries. The first-generation MSS has been underscored by L-band INMARSAT satellites providing maritime voice communication services which required larger terminals. The idea of bringing two-way voice and data at low cost to people on the move everywhere motivated the transition from analog-based INMARSAT-A to digital INMARSAT-B with a similar level of service. Faced with the growing interest in MSS, INMARSAT introduced INMARSAT-M and INMARSAT-C, supporting two-way communications and expanded services (INmarsat-Aero) while reducing ground terminal size. The terminals could be fixed, mobile, transportable, and aeronautics-based.

In an attempt to provide a rudimentary MSS, Qualcomm (joined by Omnimet Communication Services) introduced Omnitrac, a spread-spectrum two-way mobile messaging and RDSS service. Although the system was a commercial pioneer.
Table 1. Selected GEO systems. *Secondary payload.

<table>
<thead>
<tr>
<th>System</th>
<th>MSS1</th>
<th>Inmarsat-3</th>
<th>MobileSat</th>
<th>EMS</th>
<th>LEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organization</td>
<td>AMSC, TMI</td>
<td>Inmarsat</td>
<td>Optus Comm.</td>
<td>ESA</td>
<td>ESA</td>
</tr>
<tr>
<td>No. of Satellites</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satellite lifetime [yrs]</td>
<td>12</td>
<td>13</td>
<td>9</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Satellite weight [kg]</td>
<td>1400</td>
<td>1900</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Coverage</td>
<td>North America, Caribbean</td>
<td>Global</td>
<td>Australia</td>
<td>Europe, N. Africa</td>
<td>Europe, Asia</td>
</tr>
<tr>
<td>User link, Freq [MHz]</td>
<td>15645.5 – 16265</td>
<td>L-Band</td>
<td>1565–1626.5</td>
<td>L-Band</td>
<td>L-Band</td>
</tr>
<tr>
<td>Feeder link, Freq [GHz]</td>
<td>K_u-band</td>
<td>C-band</td>
<td>K_u-band</td>
<td>K_u-band</td>
<td>K_u-band</td>
</tr>
<tr>
<td>Access method</td>
<td>FDMA</td>
<td>FDMA</td>
<td>FDMA</td>
<td>CDMA/FDMA</td>
<td>CDMA/FDMA</td>
</tr>
<tr>
<td>Max data rate [kbps]</td>
<td>4.2</td>
<td>2.4</td>
<td>2.4</td>
<td>100</td>
<td>96</td>
</tr>
</tbody>
</table>

for its services, the terminal's large size and cost have made market penetration difficult. This drawback was more apparent in Europe, where a similar service was expected to be provided by GSM [9].

The cost and size of MSS terminals have plagued all MSS players, including INMARSAT, almost equally. Cost and size reduction, seen as the ticket to survival, motivated the development of the next-generation MSS from the late '80s to the present.

A summary of existing and pending GEO-class MSS systems is presented in Table 1.

The latest generation of MSS-class of INMARSATs include state-of-the-art communications satellites such as INMARSAT-3. These advanced-technology INMARSATs are referred to as the third-generation INMARSATs. The INMARSAT-3, which was launched in April 1996, is used by COMSAT (U.S. signatory to INMARSAT) to provide Planet-1 global PCS-type services in the United States [10].

The AMSC was formed by a group of eight qualified MSS applicants (competitors) to respond to the National Aeronautics and Space Administration (NASA) and the Canadian Department of Communications (DOC) MSAT program in 1984. The group (now AMSC) submitted a joint technical proposal and operating agreement to the FCC in 1988. In 1989, the Commission issued a license to AMSC to construct, launch, and operate a three-satellite MSS system. Just recently, the FCC proposed to assign AMSC the first 28 MHz of spectrum coordinated internationally in the “upper” and “lower” portions of the L-band. By awarding this spectrum, the FCC intends to guarantee the viability of GEO system as an alternative to NGSO satellites and terrestrial mobile services in sparsely populated regions of the United States [11].

Until recently, the L-S/band allocation for MSS was a subject of international controversy and stalemate for the last four years. The dispute was primarily due to the fact that the proposed bands are heavily used to support nonmobile services in many countries. In June 1996 the FCC proposal on coordinating the spectrum for GEO MSS was accepted by the United States, Canada, Mexico, Russia, and INMARSAT [12]. The Canadian counterpart to AMSC is TMI, an organization licensed to operate MSAT services in Canada.

Mobilesat, an Australian MSS, is designed to support the integrated terrestrial and satellite-based PCS type of services. This system provides dual-mode Advanced Mobile Phone Service (AMPS)/GSM services in conjunction with MSS. The Mobilesat allows use of hand-held portable, transportable, and in-vehicle mobile terminals [13].

The European response to MSS has been the creation of the European Mobile Satellite Service (EMSS). The European Space Agency (ESA), in an attempt to provide MSS, is planning to launch payload EMSS on Italsat I-F2 and payload L-band land mobile (LLM) on Advanced Relay and Technology Mission Satellite (ARTEMIS) in 1996 and 1997, respectively. The EMSS plan is to provide features and services not currently available through the emerging mobile networks, whether terrestrial or satellite-based. The EMSS regional coverage, which optimizes system performance, provides seamless coverage, service availability, infrastructural modularity and flexibility, and the capability to provide user-defined features. The EMSS communications system development is based on PRODAT (store-and-forward) and the Mobile Satellite Business Network (MSBN) (real-time) voice and data transmission systems. ARTEMIS, with its LLM payload, is an advanced-technology communication satellite equipped with the SILEX laser-optical system for interorbit, intersatellite communications [14, 15].

Communications and Broadcasting Engineering Test Satellite (COMETS) is an advanced Japanese experimental mobile satellite in the Ka-band (31/21 GHz) and Q-band (47/44 GHz) used by the Communications Research Laboratory (CRL). This satellite, which is designed to provide future MSS service, allows interorbit communications [16].

PASS (Personal Access Communication System), a NASA/Jet Propulsion Laboratory (JPL) study, also represents an advanced MSS concept aimed at providing future global PCS using K_u-band (30 GHz) on the uplink and K-band (20 GHz) on the downlink. PASS makes use of the K_u-band to offer the users more flexibility (e.g., access and mobility) [17].

NON-GEOESTATIONARY ORBIT (NGSO) SATELLITES

The NGSO satellites are emerging as major players in the world of wireless and personal communications. Big LEO

IEEE Communications Magazine • September 1996
<table>
<thead>
<tr>
<th>System</th>
<th>Globalstar</th>
<th>Iridium</th>
<th>Odyssey</th>
<th>Teledesic</th>
<th>ICO</th>
<th>Ellipso</th>
<th>Archimedes</th>
<th>ECCO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organization</td>
<td>Loral/Qualcomm</td>
<td>Motorola</td>
<td>TRW</td>
<td>Teledesic Co.</td>
<td>ICO Global</td>
<td>MCHI</td>
<td>ESA</td>
<td>Const. Comm./Telebrás</td>
</tr>
<tr>
<td>Orbital type</td>
<td>LEO</td>
<td>LEO</td>
<td>MEO</td>
<td>LEO</td>
<td>MEO</td>
<td>HEO/MEO</td>
<td>M-HEO</td>
<td>LEO</td>
</tr>
<tr>
<td>No. of orbital planes</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>21</td>
<td>2</td>
<td>2/1</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>No. of satellites</td>
<td>48</td>
<td>56</td>
<td>12</td>
<td>840</td>
<td>10</td>
<td>10/6</td>
<td>5-6</td>
<td>11</td>
</tr>
<tr>
<td>Orientation</td>
<td>Circular</td>
<td>Circular</td>
<td>Circular</td>
<td>Circular</td>
<td>Circular</td>
<td>Elliptical/ circular</td>
<td>Elliptical</td>
<td>Circular</td>
</tr>
<tr>
<td>Orbit altitude [km]</td>
<td>1414</td>
<td>780</td>
<td>10350</td>
<td>700</td>
<td>10400</td>
<td>7846-520/840</td>
<td>26,800-1000</td>
<td>2000</td>
</tr>
<tr>
<td>Satellite lifetime [yrs]</td>
<td>7.5</td>
<td>8</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>425</td>
<td></td>
</tr>
<tr>
<td>Satellite weight [kg]</td>
<td>450</td>
<td>690</td>
<td>2000</td>
<td>700</td>
<td>2000</td>
<td>500</td>
<td>425</td>
<td></td>
</tr>
<tr>
<td>Coverage</td>
<td>Global</td>
<td>Global</td>
<td>Global</td>
<td>Global</td>
<td>Global</td>
<td>Global</td>
<td>Europe, Canada, Far East</td>
<td>Equatorial</td>
</tr>
<tr>
<td>User link frequency [MHz]</td>
<td>1610−1621.35</td>
<td>2483.5−2500</td>
<td>1610−1621.35</td>
<td>2483.5−2500</td>
<td>30,000</td>
<td>1980−2010</td>
<td>L-band</td>
<td>1452−1492</td>
</tr>
<tr>
<td>Feeder link frequency [MHz]</td>
<td>76−800</td>
<td>6700−7075</td>
<td>25,100−29,300</td>
<td>29,200−29,500</td>
<td>29,200−29,500</td>
<td>5150−5250</td>
<td>15,400−15,700</td>
<td>C-band</td>
</tr>
<tr>
<td>Intersatellite links</td>
<td>No</td>
<td>Yes</td>
<td>23.18-23.8 GHz</td>
<td>Yes</td>
<td>60 GHz band</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Access method</td>
<td>CDMA</td>
<td>CDMA</td>
<td>TDD/TDMA/FDMA</td>
<td>CDMA</td>
<td>FDMA/ATDMA</td>
<td>TDMA</td>
<td>CDMA</td>
<td>CDMA</td>
</tr>
<tr>
<td>Max. data rate [kb/s]</td>
<td>9.6</td>
<td>2.4</td>
<td>9.6</td>
<td>16−2048</td>
<td>2.4</td>
<td>9.6</td>
<td>256</td>
<td>9.6</td>
</tr>
<tr>
<td>System cost $B</td>
<td>2</td>
<td>3.5</td>
<td>1.8</td>
<td>9</td>
<td>2.6</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Selected big LEOs.

MSS will, for the first time, offer affordable basic telephony to third-world developing economies that do not have the requisite telecommunication infrastructure.

**BIG LEO SATELLITES**

The evolution to universal personal telecommunication systems (UPT) defined PCS; that is, personal and terminal mobility and network transparency influenced the path of satellite communication systems in the late '80s and early '90s. The development of big LEO satellites to provide voice and data communications to the mobile user with handheld terminals is within this UPT class context. A summary of big LEOs' characteristics for the proposed systems and those under construction is shown in Table 2. In response to the increasing demand for NGO operating licenses, in January 1995 the FCC International Bureau authorized Loral/Qualcomm (Globalstar), Motorola Satellite Communications (Iridium), and TRW (Odyssey) to construct, launch, and operate their systems using LEO and MEO orbits. The Commission extended additional time to two other applicants, Constellation Communications and Mobile Communications Holdings (Ellipso), to establish their qualifications. The Globalstar system supports dual-mode operation that will allow users to have transparent access to satellite as well as land-based cellular networks in 73 countries. While Globalstar, Iridium, and Odyssey support low-rate, Teledesic provides high-rate broadband data services to mobile units equipped with additional tracking Ka band antennas. Teledesic is different from the other big LEOs in the sense that it is primarily intended for broadband fixed wireless data communications (i.e., satellite-based broadband integrated services network — B-ISDN) [18]. Teledesic and Iridium have direct intersatellite communications link (ISL) capability, which is independent of the ground segment. Direct ISL capability allows Iridium to provide telecommunication services in countries without existing wireline infrastructure and switching networks. In 1995, Inmarsat played a major role in the creation of ICO (formerly referred to as Inmarsat-P) through its Project-21 initiative. The goal was to bring to the global marketplace PCS-class services using pocket-sized handheld terminals by the turn of the century. The system will support integrated satellite-terrestrial (e.g., GSM) communications. The target customer set for ICO, as well as all other big LEOs, is expected to include international business travelers, domestic national roamers, cellular users (as an augment), long-haul transport and aeronautical applications [19].

The Ellipso system is based on two coordinated subconstellations to achieve maximum coverage. The Ellipso Borealis subconstellation has ten satellites in two elliptical planes to serve northern latitudes. The Ellipso Concordia subconstellation is circular MEO with six satellites to serve tropical latitudes [20]. The Archimedes is an ESA-sponsored program to demonstrate the feasibility of HEO multiregion services using the concept of multiregional highly elliptical orbit (M-HEO). M-HEO is a constellation of six satellites orbiting in three planes at perige of 1000 km and apogee of 27,000 km. In addition to MSS, this system can provide high-quality global direct satellite radio broadcasting (DBS-R) services [21]. The ECCO system is a joint project between the Brazilian and American partners to combine ECO-8 and Constellation systems aimed at providing MSS to the remote and sparsely populated regions of the tropics.
LITTLE LEO SATELLITES

The trend toward constellations of much smaller satellites as a cost-effective system solution for the specific application of low data transmission is exemplified by little LEOs. Table 3 describes characteristics of some selected little LEOs: Orbcomm [22], Starsys [23, 24], VITA/Sat (Volunteers In Technical Assistance) [25], and GEMnet [26]. Among other U.S. entrants are E-Sat, Final Analysis Communication, and LEO One USA. European systems include ITAMSAT (amateur, Italy), Ariane Radioamateur Satellite Enseignement Espace (ARSENE) (amateur, Centre National d'Etudes Spatiales—CNES, France), and IRISS-ILMS (ESA). The distinct feature of little LEO satellites is the use of the very/ultra high frequency (VHF/UHF) band that accommodates inexpensive transmission hardware.

REMARKS

This article provides an overview of the existing and future mobile systems within a context of evolving global PCS UMTS requirements. It was shown that different classes of mobile satellite systems may be categorized based on orbital deployment, spectrum allocation, and end-user service provisions. The information provided in this article can serve as a reference for designers and planners in the mobile satellite industry, as well as other interested readers [27].

REFERENCES

[19] Inmarsat WWW page.

BIOGRAPHIES

FABRIO ABISHIN was born in Italy and received the B.S. degree from the University of Maryland, College Park, and the M.S. degree from the University of Southern California, Los Angeles, both in electrical engineering. From 1995 until 1999 he was with Technology Group working on advanced digital mobile communication systems. He joined Bell Laboratories in 1999, where he has been involved in the research and development of spread-spectrum digital cellular portable telephones. His research interests include coding, modulation, spread spectrum, and wireless cellular communications.

ZORAN SVEKOL received the Dipl.Ing. degree from the University of Belgrade, and the Ph.D. degree from the City University of New York, both in electrical engineering. He is an assistant professor in the Department of Electrical and Computer Engineering at New Jersey Institute of Technology (NJIT). His research interests are multiuser detection, wireless cellular systems, and modulation and coding techniques.